CAUSES OF THE NOISE OF ELECTRICAL MACHINES

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There are two main reasons why the noise problem is pressing in the manufacture of electrical machines. The first is due to the fact that with the technology and material at present available, it is possible to produce machines of a given physical size which produce a much greater effect than formerly. The other is due to the extensive use of machines at places where silent running is required in view of the surroundings. This article deals exclusively with the sources of noise from the electrical machines themselves, i.e. not with the question as to how the noise is propagated from the machines through pipes, foundations, etc.

There are many obvious causes why electrical machines send out noise. Most of them are rotary machines, consequently the rotors must be mounted in bearings, ball-bearings or plain bearings being used as a rule. Both types may give rise to noise, called bearing noise. To ensure satisfactory cooling of the machines, rotary fans are provided which force or draw air through the machines. Very often, especially at high peripheral speeds, the fan system gives rise to noise production - fan noise.

The bearing noise and ventilation noise together with the noise caused by poor dynamic balancing of the rotors, which first and foremost shows itself in vibrations or drag between stator and rotor parts, are referred to as purely mechanical noise. The purely mechanical noise may be defined as the noise which is produced when the rotor is driven at the normal r.p.m. without the machine being connected to the mains.

The other group of noise sources in the machine is called magnetic noise, and has its origin in the electromagnetic phenomena which occur in machines when the latter are connected to voltage.

Finally, there is as a rule a reaction between the mechanical construction of the machine and the above-mentioned electromagnetic phenomena, which often increases the noise from machines. For example, the force reaction between stator and rotor may appreciably increase the mechanical bearing noise.

The sound phenomena due to unbalance of the rotor or to contact between rotating and stationery parts of the machine are trivial, in that they can be avoided. On the other hand, there is just reason to consider bearing and ventilation noise more closely.

In Europe, we use ball-bearings and roller-bearings in electrical machines as extensively as possible, since this is cheaper than using plain bearings. In America, conditions are quite different; there it is considered that they can provide plain bearings cheaper than ball-bearings. It is usually good practice to use plain bearings if a light weight machine is required; that is always correct, but we must not forget that a good fit is necessary to avoid bearing chatter. If there is bearing chatter of if the bearings are not exactly in line so that the shaft is under stress, one can obtain at least just as much noise from plain bearings as from ball bearings. This is to some extent connected with the magnetic forces of attraction in the machine, which we shall discuss later.

It is naturally most convenient to use ball-bearings because they practically require no inspection. It is very common practice to produce the smaller machines with ball-bearings, without grease cups. In slightly larger machines, valve lubrication is used extensively, this preventing the ball race from becoming too full of grease.

After the war, the use of small motors increased considerably. Both Titan and Thrige established new departments for the production of small motors, also A.S.E.A. and many other foreign manufacturers. A large number of these small motors are used at places where little importance is laid on their being as silent as possible. Such uses include refrigerators, pumps, especially heat transferring pumps and many others. It is no light matter to make these small motors perfect. Much can be obtained by keeping to the tolerances in manufacture. Even if we take the greatest care in this respect, there will always be some deficiency. Competition compels manufacturers to utilise machines as much as possible. Formerly, when more material was used per effective unit, the noise problem was just as pressing. The Americans always use comparatively more material in their small motors than we do; this applies particularly to single-phase motors. For small motors, we can say with good approximation that silence is directly proportional to the weight and price. There are a number of interesting devices which can improve the silence, including the use of "herringbone patterned" rotors, but it would depart too far from the scope of this article to go into this point. We shall therefore revert to the subject of ball-bearings.

Anyone who has attempted to assemble a small asynchronous motor will have noted that by striking the bearing shields at suitable points with a rubber hammer it is possible to alter the character of the noise very considerably. A similar effect can be

obtained by loosening one of the bolts which tighten the shields and housing together and possibly by inserting a screw driver in the recess. This phenomenon may be due to many things, including stresses in the material, but it may also be due to the fact that the outer and inner races in the ball-bearing have shifted relatively to each other in assembly. I once made a small experiment which shows the connection between the intensity of the ball-bearing noise and the angular displacement between outer and inner races.

Figure 1 shows the apparatus used. A beam of light from a light source L is projected on to a narrow mirror secured to the outer race of the ball-bearing, and thence to a scale mounted at a suitable distance so that the angular displacement between the outer and inner rings can be measured. By means of a sound pressure meter, the correlated values of angular displacement and sound pressure are obtained. Figure 2 shows a curve obtained in this way. The increase of 9 phons from the correct position of the races to the maximum angular displacement occurring in this case corresponds to a doubling of the noise.

This little experiment thus shows that specially silent ball-bearings should be carefully mounted if there is going to be any object in using them. In addition to the common types of ball-bearings, it is possible to obtain selected ball-bearings (SKF refer to them as C.156); for these bearings, the tolerances are particularly small. These are generally better than ordinary bearings from the point of view of noise, even if the difference is not remarkably great. The SKF have done much work in the manufacture of silent ball-bearings; a method has been found for producing more silent bearings. The method is based on the production of "rounder" balls than formerly. It is also the opinion that this new method of machining the balls will also be applied to ordinary bearings.

An innovation, which has found extensive application in America, are "prelubricated sealed bearings". The balls are entirely enclosed in grease which should last for 20 years. There are two reasons for welcoming these bearings. Firstly, it is impossible to get dirt in them during the mounting of the motor, and secondly it is possible to dispense with the inner lining of the bearing casing. Figure 3 shows their appearance. I am aware that they have not found extensive use in Europe, but some German firms are using them.

It may be of interest to compare the frequency analyses of the noise from the same type of motor provided with ball-bearings in one case and with plain bearings in another. Figure 4 shows such a curve for a 3 H.P. motor. The difference is appreciable, especially at the higher frequencies.

With regard to ventilation noise, this can often be appreciably reduced by appropriate modification of the passage of the ventilation air through the motor. An example will show this.

It concerns a 6-pole 900 H.P. slip-ring motor for driving a water pump. The motor was not accepted on delivery on account of the noise which it made. Figure 5 shows the sound distribution round the motor and pump on delivery. In the subsequent sound frequency analysis, it was found that there was a pronounced fan noise around 2000 cycles. The motor was a 6-pole motor and there were 126 slots in the rotor, this gave a siren note of the indicated frequency when the ventilation air was forced from the radial ventilation channels of the rotor to the corresponding channels of the stator via the air gap. The peripheral speed of the rotor was 46 metres per second, and as shown by Figure 6, the distance between the slot wedges in the stator and rotor was only 3 mm. By increasing this distance to 11 mm. A reduction of the siren sound was obtained as shown in Figure 7. Figure 8 shows the noise distribution round the motor and pump after the modification. The motor was then accepted, since the motor and pump had the same noise level.

In addition to mechanical noise sources in machines, there are also magnetic sources of noise. The fact that the machine when in operation is connected to a certain voltage which sets up a field in the machine, means that there are certain electromagnetic forces of attraction between the stator and rotor, these forces having different pulse frequencies capable of setting the mechanical parts of the machine in vibration, so that they emit noise. For A.C. machines, we think first and foremost of the demagnetising frequency which is double that of the mains, i.e. 100 cycles. For rotary machines, however, this frequency generally plays a very small part, <u>inter alia</u> because the ear is very insensitive in this range. For transformers, on the contrary, the demagnetising frequency may play a very prominent part - it is mostly in America that we have heard of this phenomenon, i.e. frequencies of 120 cycles because of the mains frequency of 60 cycles. In demagnetisation there occur certain magnetostriction alterations in the laminations causing the surface of the iron core to oscillate in rhythm with the demagnetisation and thereby to emit sound, which in the case of the large surfaces involved in transformers may attain very considerable intensities.

In rotary electrical machines there is, as is well known, an air gap between the stator and rotor. These air gaps are of different dimensions and appearances for the different types of machines. For d.c. and synchronous machines, relatively large air gaps are used. In these machines, there is a special winding for magnetisation. Matters are different with a synchronous machine . Here the magnetisation is produced by the interaction between the magnetomotive forces of stator and rotor windings, so that the general tendency is to make these machines with as small an air gap as is compatible with the mechanical construction.

As regards A.C. machines, the tendency is to produce an air-gap field which is as nearly sinuosoidal as possible. From a study of electrical machines, it will be known that an infinite

number of phases and an infinite number of slots ought to be employed in order to obtain an absolutely sinusoidal field in the air gap. This of course cannot be done in practice, one must use a finite number of phases, as a rule three phases, and a finite number of slots, usually a whole number of slots per pole and phase, giving what is called a regular winding, in contrast to irregular windings with a fractional number of slots per pole and phase. I shall not consider irregular windings, merely interposing the remark that such windings may give rise to very irregular vibration and noise phenomena in machines; in general, this kind of winding should not be used in asynchronous machines if it can be avoided in any way. This type of winding is often used in synchronous machines, but the air gap, as mentioned above, is large and will therefore diminish or eliminate entirely any vibrations.

We shall now revert to the regular windings. We can conceive making a frequency analysis of the curve form for the air gap field either by measurement or by Fourier analysis. In addition to the main field corresponding to the fundamental frequency, we shall find a multitude of higher harmonic fields of various origins. Some arise from sub-division into a finite number of phases, the so-called band harmonics; some arise from sub-division into a finite number of slots; these are called slot harmonics or tooth harmonics. The magnitude of the former category is mainly determined by the applied voltage, but the magnitude of the second category depends upon the ampere turns in the machine. In asynchronous machines both the stator and rotor gap surfaces are divided into slots. The air gap field is determined by the resultant magnetomotive force and the permeance of the air gap (magnetic conductance of the air gap). The resultant magnetomotive force has in itself a double infinity of higher harmonics; if a Fourier analysis of the air gap permeance is carried out, this gives a single infinity of higher harmonics. It will be seen from the foregoing that the resultant air gap field comprises a treble infinity of higher harmonic fields. Fortunately, they are far from being all of equal importance. In smaller asynchronous machines, one should in the first place guard against the first tooth harmonic, and if the machines are very saturated, the saturation overtones should also be watched. For rather larger machines, other fields are included which can make a machine practically useless. This may be explained as follows: There may occur force components which arise from the reaction between stator and rotor fields and which have a wavelength of the same order of magnitude as the principal dimensions of the machine. The force frequency may be so high as to be of the same order of magnitude as the natural frequency of vibration of the packet of stator laminations for deformations with 6 or 8 modal points.

The production of these high-frequency long wave fields may occur as follows (Figure 9). We have a field from the stator with p pairs of poles, a field from the rotor with p + 1 pairs of poles, these two fields will give two curves of force

distribution, one a short wave and the other a long wave (it will be recalled that the force reaction is directly proportional to the square of the field). The frequency depends upon the speed at which the two waves move relatively to each other. With the given numbers of pairs of poles, the long-wave force distribution will oscillate about 4 nodal points. If now the force frequency lies close to the natural frequency of vibration of the packet of stator laminations for a deformation with 4 nodal points, resonance will occur, i.e. a very small effect will produce intense vibration; the weaker the frame of the stator, the more powerful will be the vibrations produced. The resistance to these vibrations is directly proportional to the third power of the height of the frame. Figure 10 shows the different ways in which a stator packet of laminations can oscillate. A natural frequency of mechanical vibration corresponds to each form of oscillation.

Formulae may be derived for calculating these natural frequencies of mechanical vibration. This has been done by a German author, Dr. Heinz Jordan A.E.G, in his book "The Noiseless Electric Motor". Some will wonder why there are such sharp natural frequencies that one can state directly a narrowly limited frequency range from which one should try to keep away the magnetic force frequencies. Here again I will refer to an experiment I made a couple of years ago.

Round a stator tooth in an otherwise unwound stator some turns were made which, after the stator had been mounted with the rotor and bearing shields, had a constant current applied to them with a variable frequency 0-1500 c.p.s. corresponding to a force pulse varying from 0-3000 c.p.s. A frequency analysis at the point of the stator packet shown in Figure 12 gave a result which is partly shows in Figure 11. The resonance vibrations occur at about 400 c.p.s. and 900 c.p.s. corresponding to vibration modes $r = 2$ and 3, respectively. As follows from Figure 11, there are well-defined natural frequencies for the packet of laminations. In practice, care should be taken as far as possible to ensure that the magnetic force frequencies lie at an interval of ± 25% from the natural frequencies. That it is actually a question of deformation modes of the type stated follows from Figure 12 which shows oscillation amplitudes of constant impressed resonance frequency measured radially at the bottom of the stator slots.

By including the mechanical system in the considerations of the magnetic noise from machines we have in fact provided an explanation of why a definite slot combination is important for a certain size of machine, whilst for another size of machine it is practically useless.

We can indeed predict what the magnetic noise of a machine will be like. The agreement between the prediction of noise and the noise in testing the machine is remarkably good.

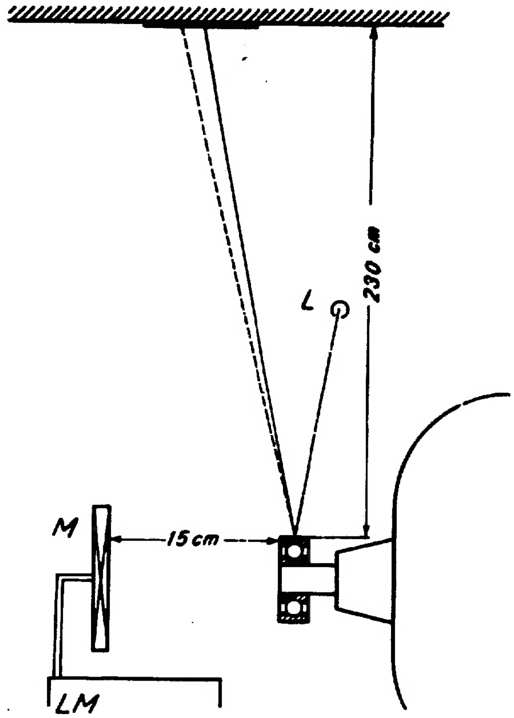
As is well known, after the war, it became general to use directionally oriented laminations in transformers, whereby the efficiency (kva/kg) was very considerably increased. If we are one day contronted with the same jump in efficiency of rotary machines the stator frame will be so weak that it is to be feared from the purely mechanical standpoint and in any case with regard to the noise effect, they will require extremely careful dimensioning, if the result is to be satisfactory.

The examples referred to here concerned asynchronous machines, since this is the most difficult type of machine to cope with in regard to noise, whilst being of course the commonest type of machine. This does not mean that there are no noise problems in d.c. machines and synchronous machines. In the submarine for example, it has been a very anxious matter to obtain sufficiently silent d.c. machines so as not to disclose the position of the boat by the propagation of sound through the water.

For synchronous machines, it is not uncommon in any case at water power stations, for there to be difficulties with room resonances such that it is very uncomfortable to remain in the machine room. As a rule, the buildings are ferro-concrete and therefore are also "hard" from the acoustic point of view.

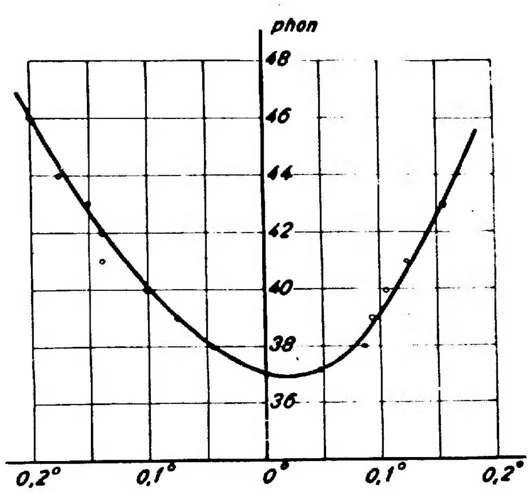
In conclusion, it may be mentioned that lift motors are frequently subject to criticism on account of their noise. This noise occurs during acceleration and possibly also retardation. The mechanical electro-magnetic resonances referred to above play no small part. When an asynchronous motor is speeding up, there is often produced a whining note which rises and falls in intensity when the machine is in the vicinity of its top speed; it is very often when the tooth frequency is passing through a region where resonance with the mechanical natural frequency occurs.

It will be gathered from the foregoing that there are various causes for the noise emitted by electrical machines, and that the problems encountered in combating noise are not always so simple to solve as one may perhaps believe. There are many places where the demand for noiselessness is absolutely justified. There are, therefore, good reasons for investigating the problems further, even if in this case, as in many other spheres, it is a matter of finding the correct compromise between the factors concerned.



Measurement of ball-bearing noise

Fig. 1: Experimental arrangement for measuring the connection between noise and the angular displacement of outer race relatively to inner race.



Angular displacement of outer race relatively to inner race.

Fig. 2: Measured curve of the connection between angular displacement and noise.

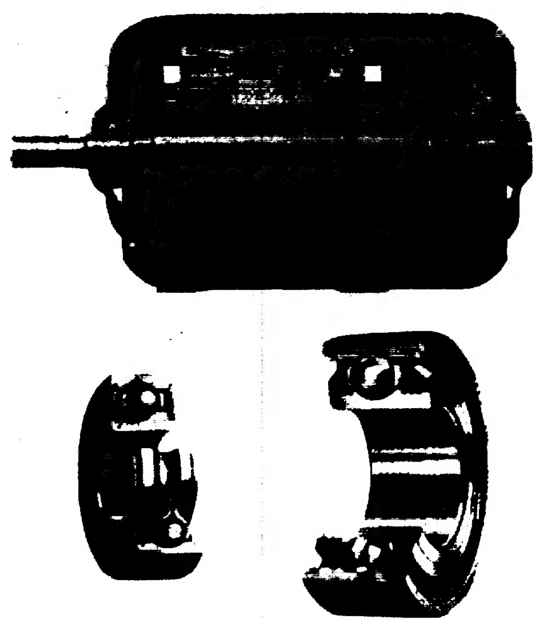


Fig. 3: Types of 'prelubricated sealed bearings' and their mounting in a motor.

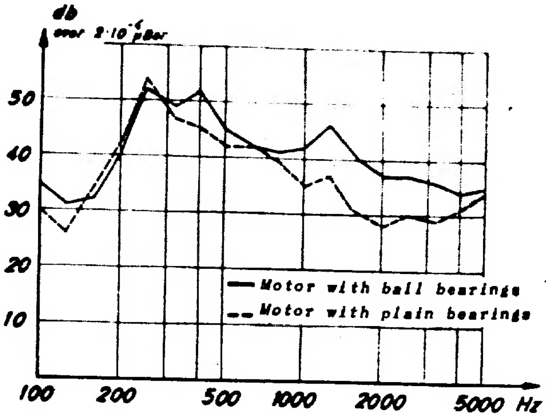


Fig.4: Frequency analysis of noise from ball bearings and plain bearings.

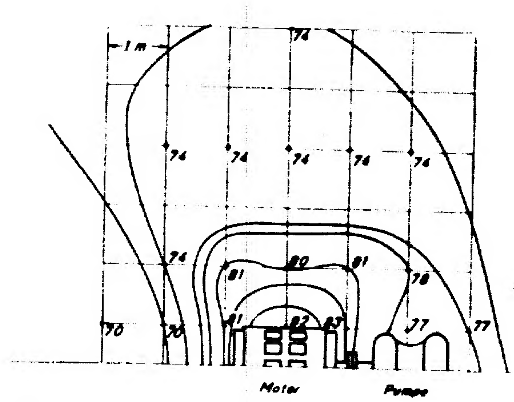
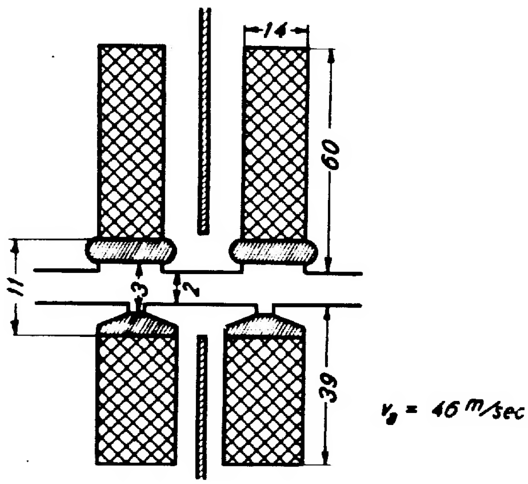


Fig.5: Sound distribution round motor and pump on delivery.



Radial section through air channel

Fig.6: Radial section through ventilation channels

MA 117– 900 HK — 6pol.

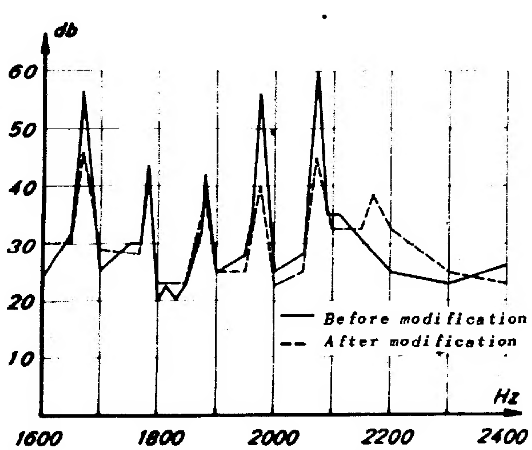


Fig.7: Frequency analysis before and after modification.

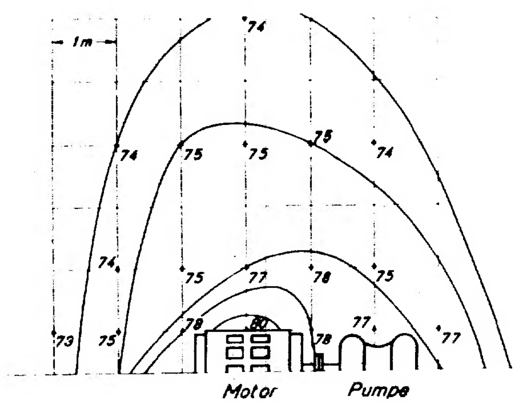


Fig.8: Sound distribution round motor and pump after modification.

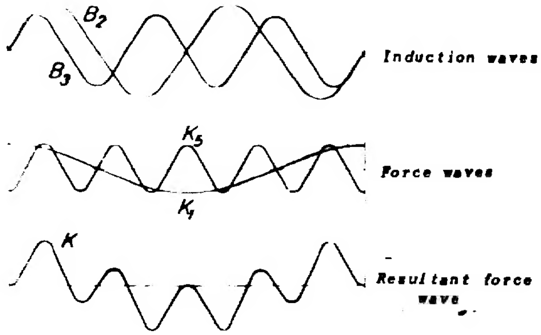


Fig.9: Induction and force wave distribution

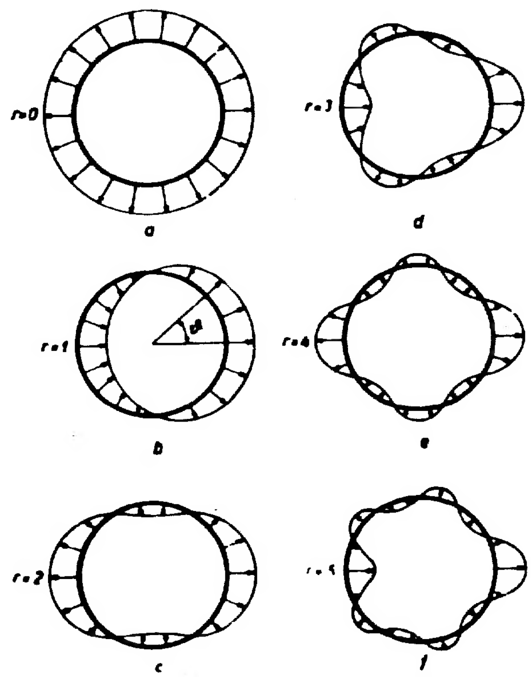


Fig.10: Vibration modes of stator laminations.

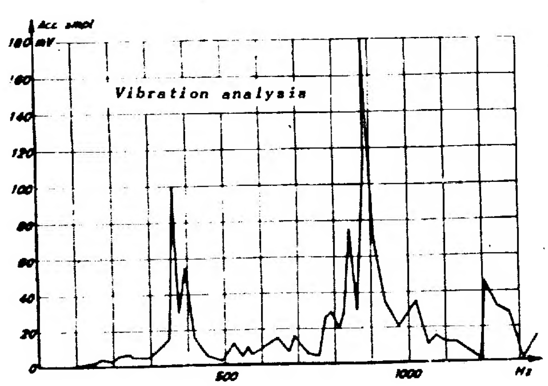


Fig.11: Vibration analysis of stator lamination vibrations with impressed variable force frequency.

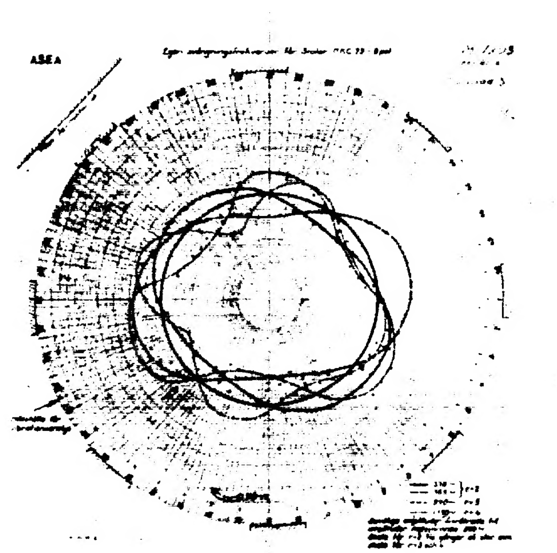


Fig.12: Vibration amplitudes with constant impressed resonance frequency.